Design and Evaluation of Enhanced Dielectric-Barrier-Discharge Actuators

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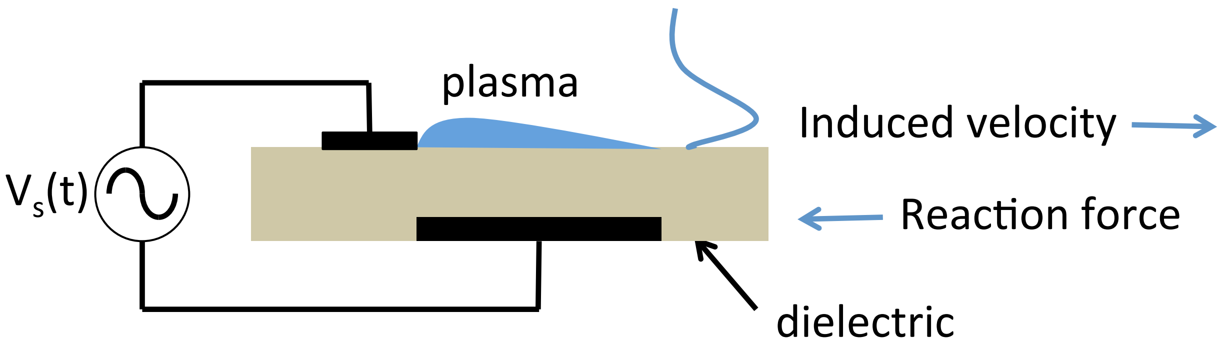
Dielectric Barrier Discharge Actuator



Non-thermal, non-equilibrium plasma

Typical Dielectric Barrier Discharge on Glass
f=5 kHz

Outline

- Relevance to NASA Aeronautics
- Description of effort's scope and rationale
- Experimental effort (dielectric and DBD force data)
- Alternative 1-D volume discharges
- Conclusions

Can DBD Actuators Support High Reynolds Number Flight Flow Control?

- While electronic DBD flow control is currently a relatively weak effect, its robustness, controllability and simplicity could make it valuable option for future generations of aircraft.

- In order to fulfill that vision, pursuit of new innovations and understanding physical mechanisms must proceed.

Leveraging Activities

- **NASA Aeronautics Research Institute (NARI) Seedling Award**
  - "Enhanced Dielectric-Barrier-Discharge Body-Force Generation Using Nanofoam Materials" – Phases 1 & 2
  - NARI seeks and develops new and promising aeronautics ideas for transfer to mainline project funding.
  - Current Goal: Explore materials of varying microstructure and chemistry, particularly **aerogels/nanofoams,** for enhanced performance of DBD flow control actuators.
- **NATO STO/CSO AVT-190 – "Plasma Based Flow Control for Performance and Control of Military Vehicles"**
  - Goal: Provide DBD code validation data (thrust, velocity) agreed upon by multiple NATO and PfP (Partners for Peace) participants.

Dielectric Terminology

Poisson's equation drives DBD electrostatic forces

$$\overline{\nabla} \bullet \overline{D} = \rho_c$$

Definition of displacement field

$$\overline{D} = \varepsilon_o \overline{E} + \overline{P} = \varepsilon_o \varepsilon_r \overline{E}$$

P = polarization field
D = displacement field
E = electric field

ε_0= permittivity of free space
ε_r = relative permittivity of material
ρ_c=charge density

Force Enhancement with Low Permittivity Dielectrics

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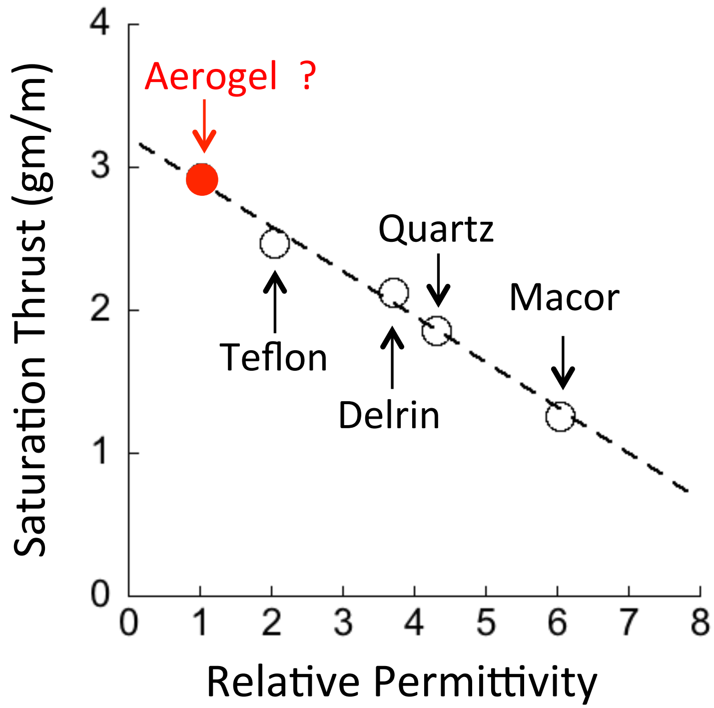
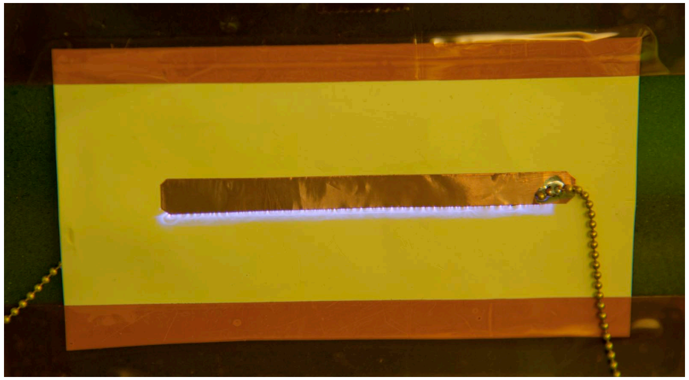


Adapted from :
Thomas F., et. al., AIAA J., 2009 and
Durscher, R. and Roy,S., J. Phys. D: Appl. Phys., 2012

NASA/GRC Polyimide Aerogel*



Aerogel Supports DBD Plasma

*https://technology.grc.nasa.gov/featured-tech/aerogels.shtm

Force Enhancement with Surface Coatings

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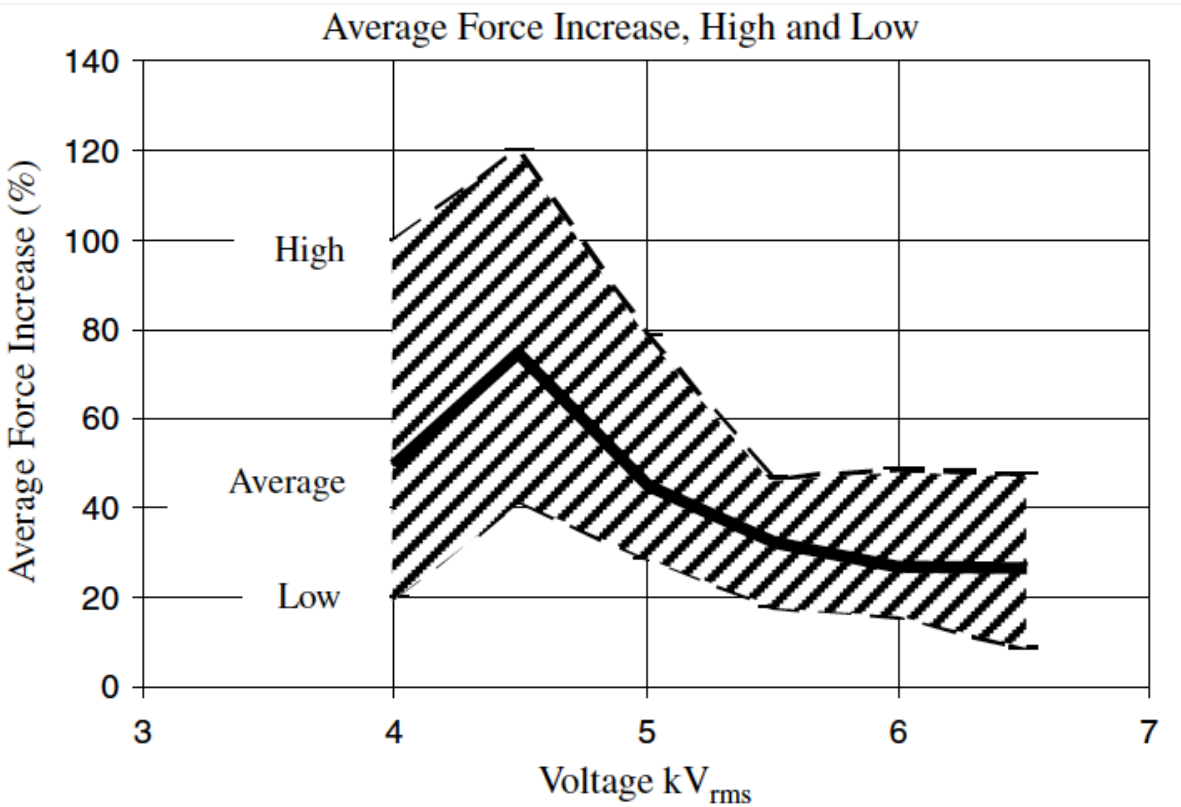

This may be a humidity effect and not a catalytic phenomena

Titanium Oxide: Photocatalyst and Wide Band-Gap Semiconductor)

From: Fine and Brickner, AIAA J., No. 12, Dec 2010

Guiding Questions

- Are some materials superior to others in their ability to mediate creation of DBD body force?
- What is the role of microstructure and chemical composition?
- How do volume and surface properties affect performance?
    - Permittivity and dissipation
    - Secondary electron emission (SEE)
    - Catalytic/photocatalytic effects
    - Surface conductivity and chemical coatings
        - Surfactants (anionic, cationic, non-ionic)
        - Antioxidants (radical scavenger)
        - Adsorbed moisture (relative humidity)

Goals

1. Characterize a variety of existing dielectric materials seeking to explain differences in body force generation using:
   - Dielectric properties
   - Reaction force
   - Electrical charge transfer
   - Lumped-parameter 1-D circuit simulations
2. Use this information to develop new materials optimized for DBD applications

Equipment for Materials Characterization

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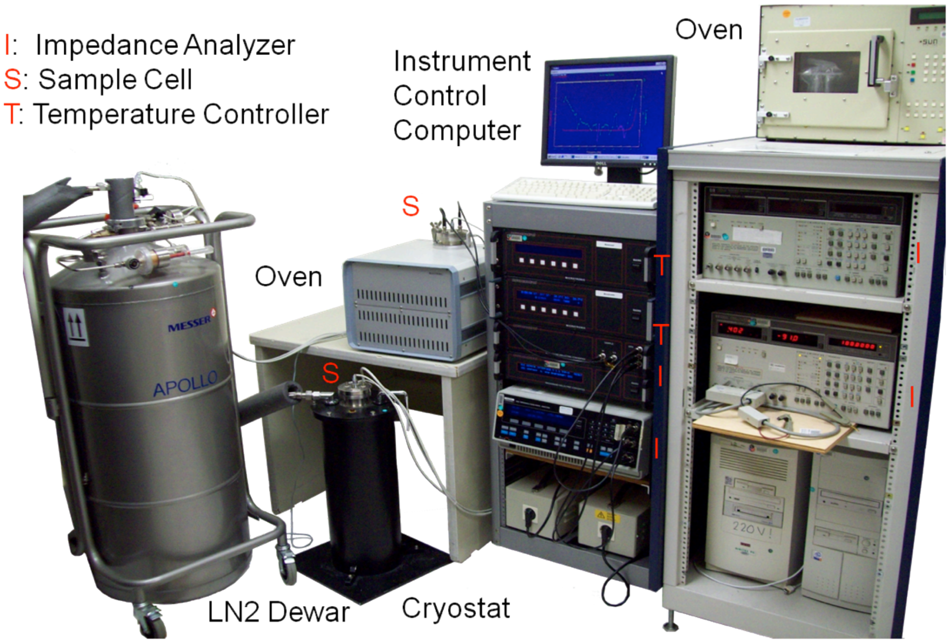
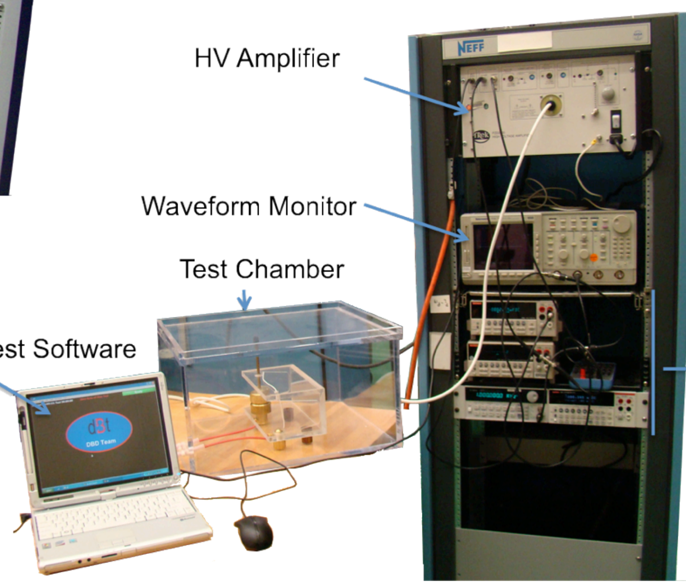


Dielectric Constant and Loss Tangent

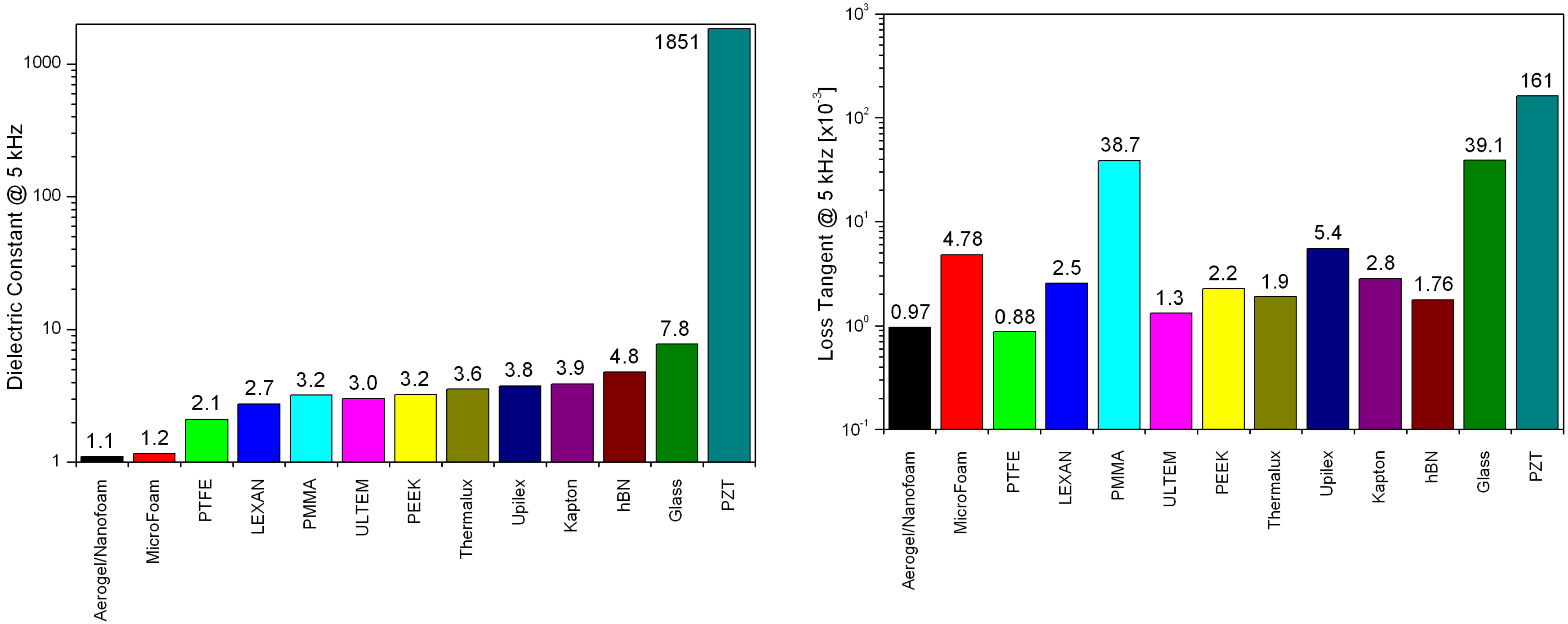


Dielectric Breakdown Strength

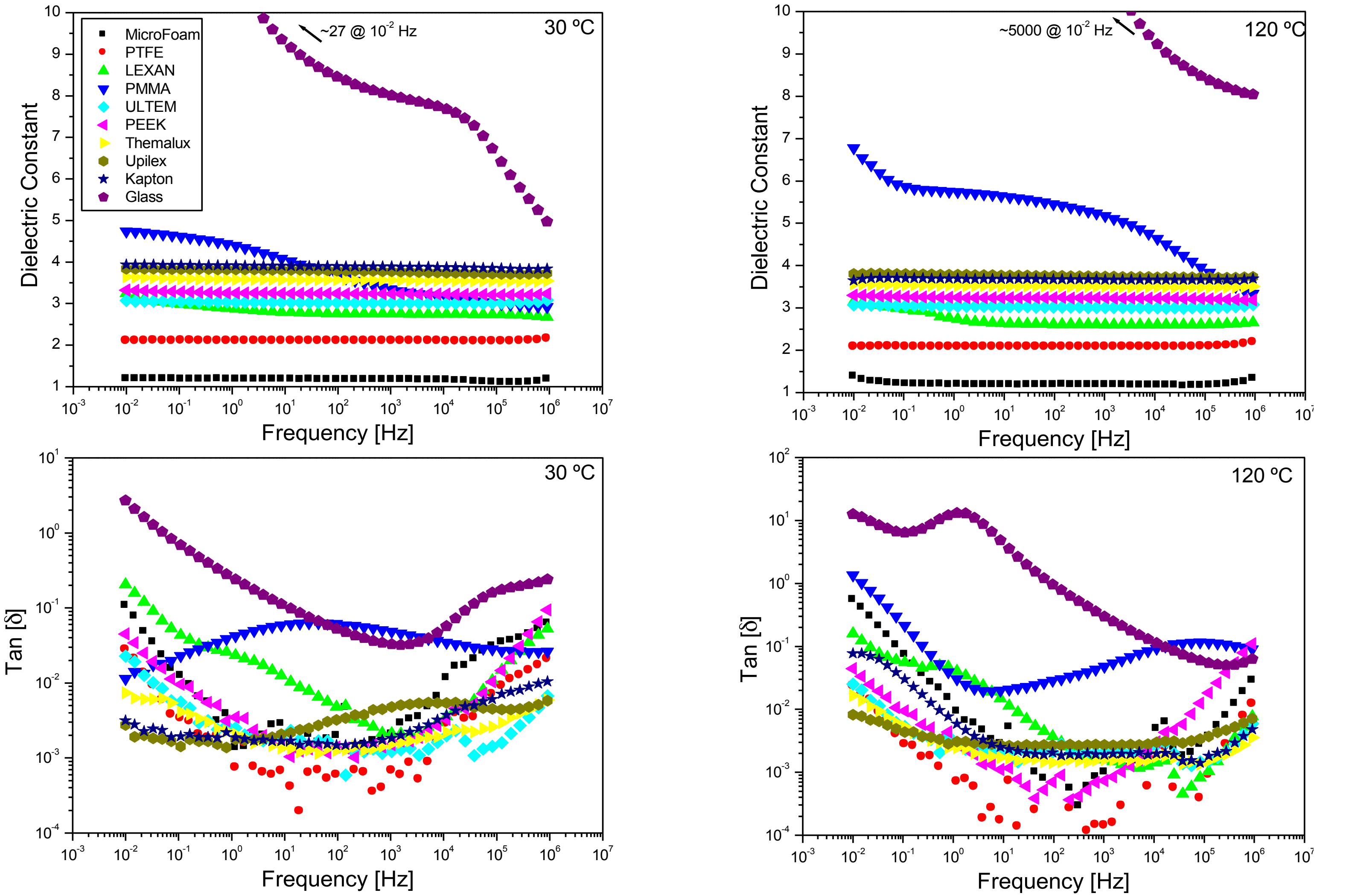
Measured Dielectric Constant for Various Materials

NASA Aeronautics Research Institute

Desired properties:
Low dielectric constant and loss



Measured Dielectric Constant for Various Materials



DBD Thrust Measurement Equipment

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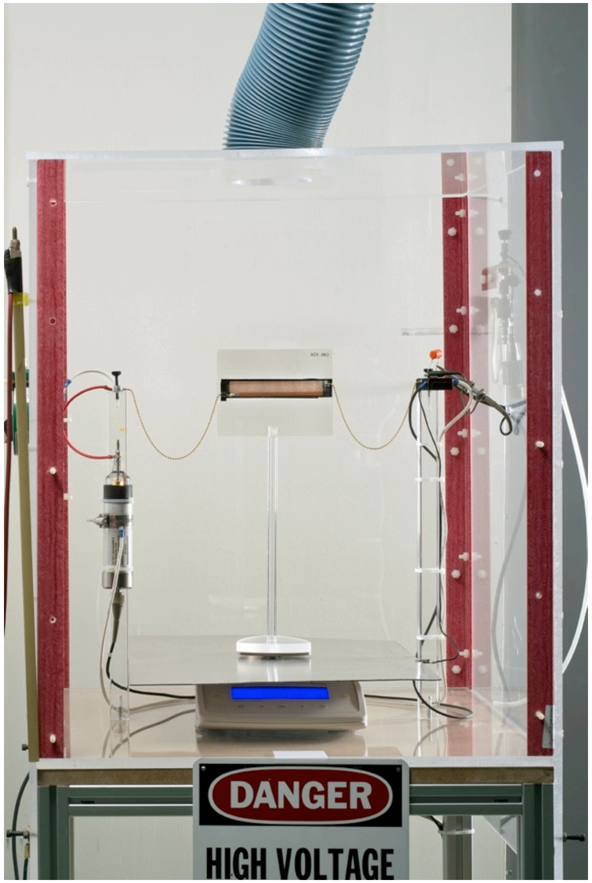
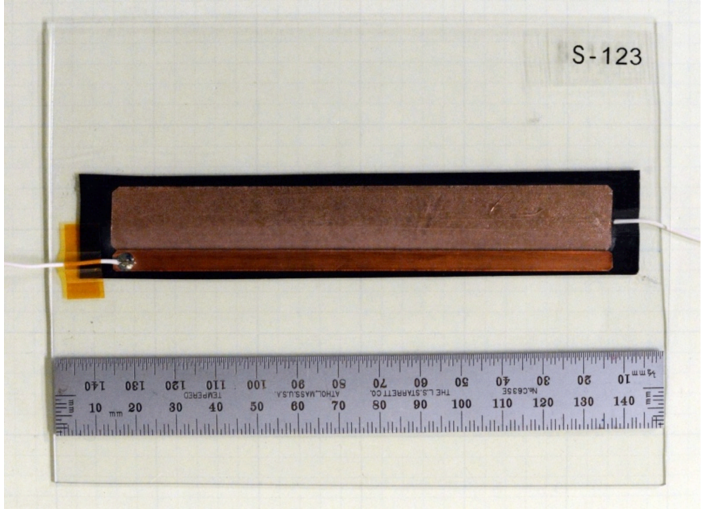


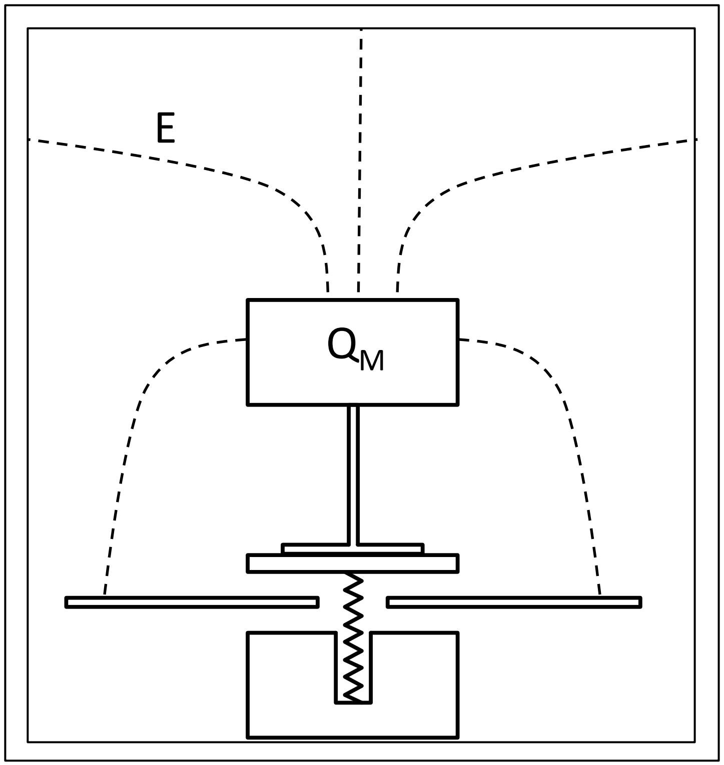
FPCB DBD Thrust Stand



Typical DBD Model

Original Thrust Stand, USAFA, 2005

Error Due to Electrostatic Induction Between Model and Surroundings



Force balance and shield grounded

- Model with charge Q_M is in electrostatic force equilibrium with surroundings.
- Uncontrolled physical or electrical (charge) changes may lead to measurement error.
- Humidity in the enclosure has a large, first order effect on DBD force.

Effect of Relative Humidity: Clean Glass Substrate

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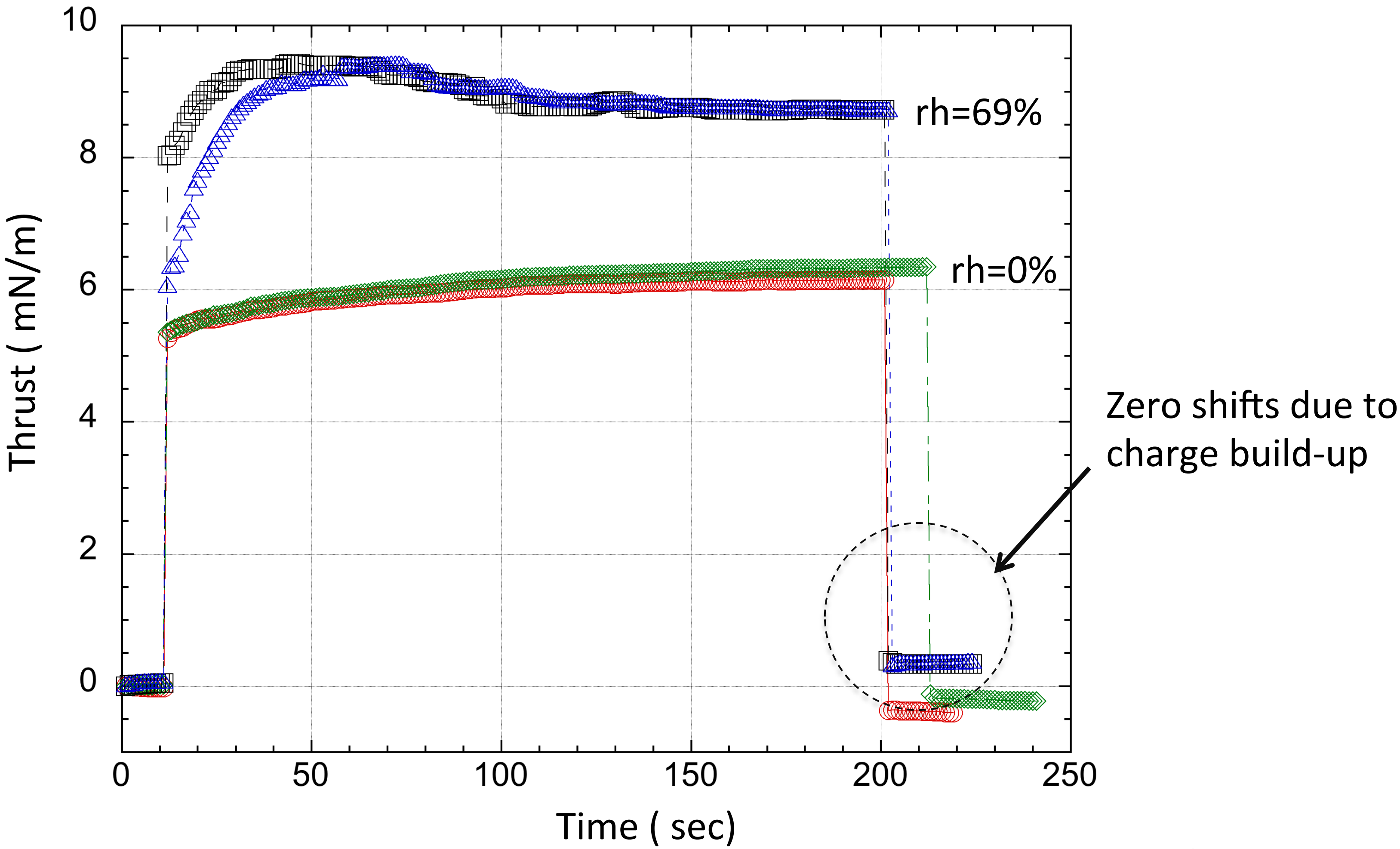
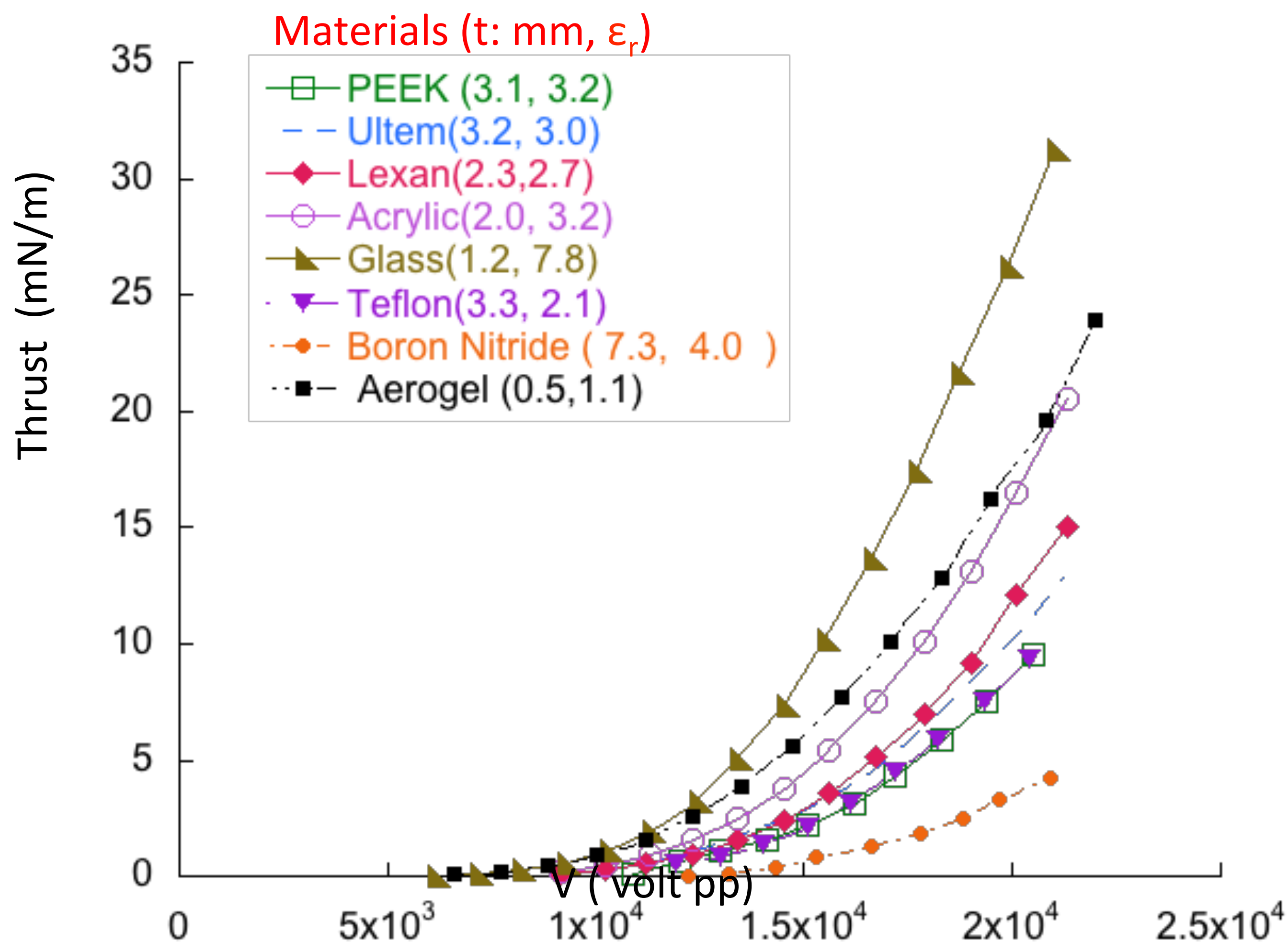
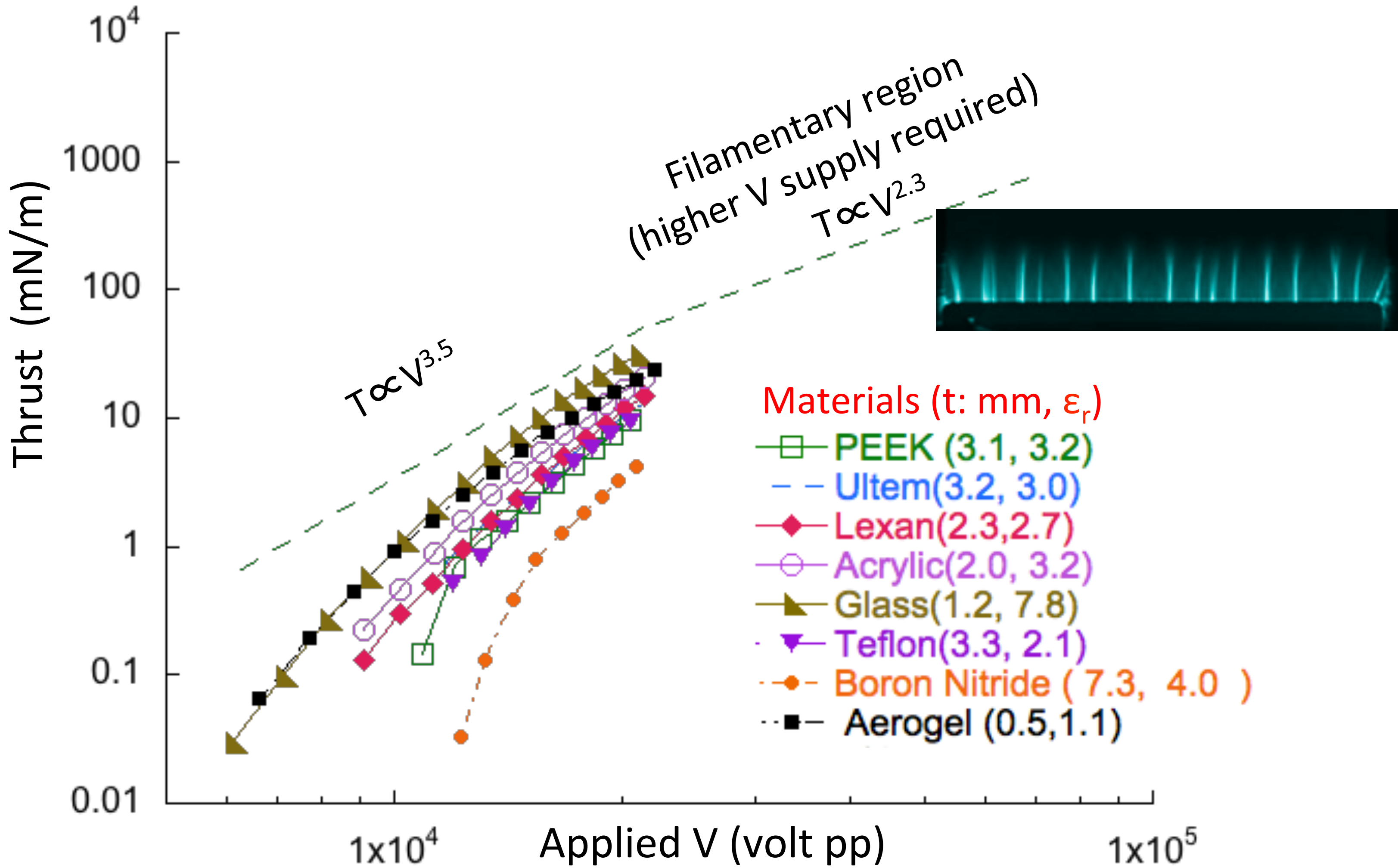


S-125

Thrust Data for Dielectric Materials



Thrust Data for Dielectric Materials



thrust all lin 2

1D Volume Discharge May Offer Advantages for Dielectric Testing

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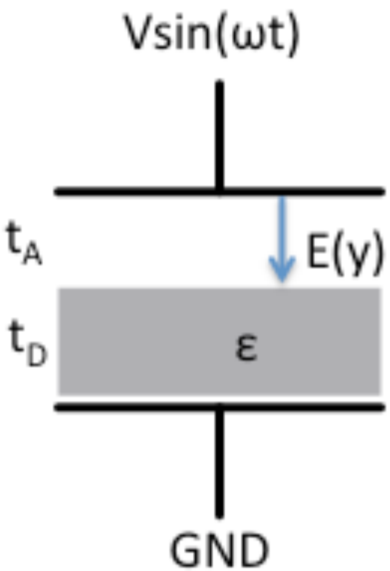
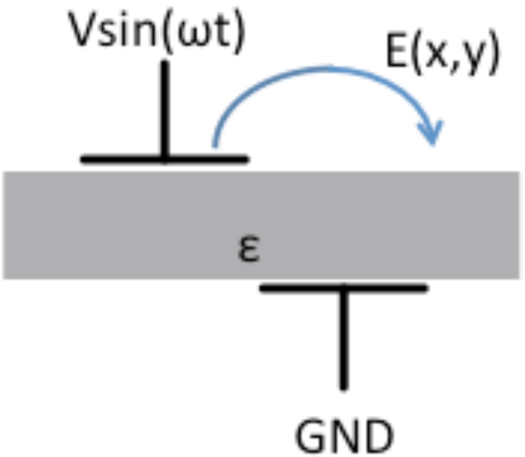
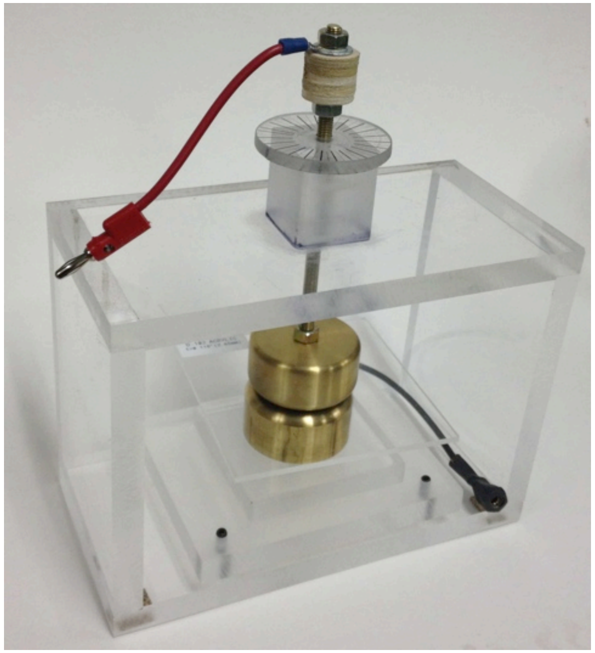


Volume Discharge
(One-dimensional)

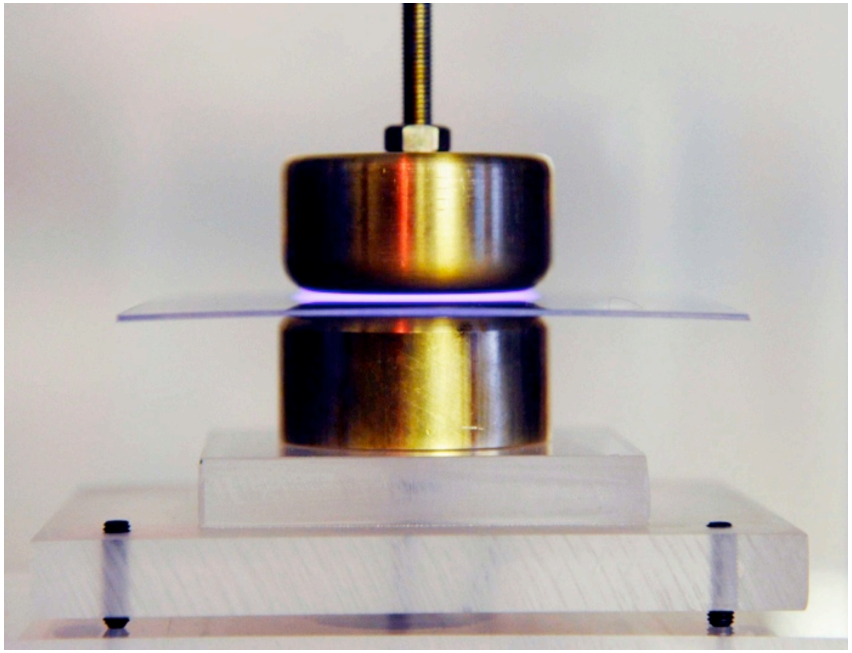


Surface Discharge
(Two-dimensional)

One Dimensional Volume Discharge Apparatus



Variable gap volume discharge tester



Typical DBD volume discharge

Typical 1-D Cyclogram

Acrylic, thickness=0.94 mm, er=3.2, f=1 kHz

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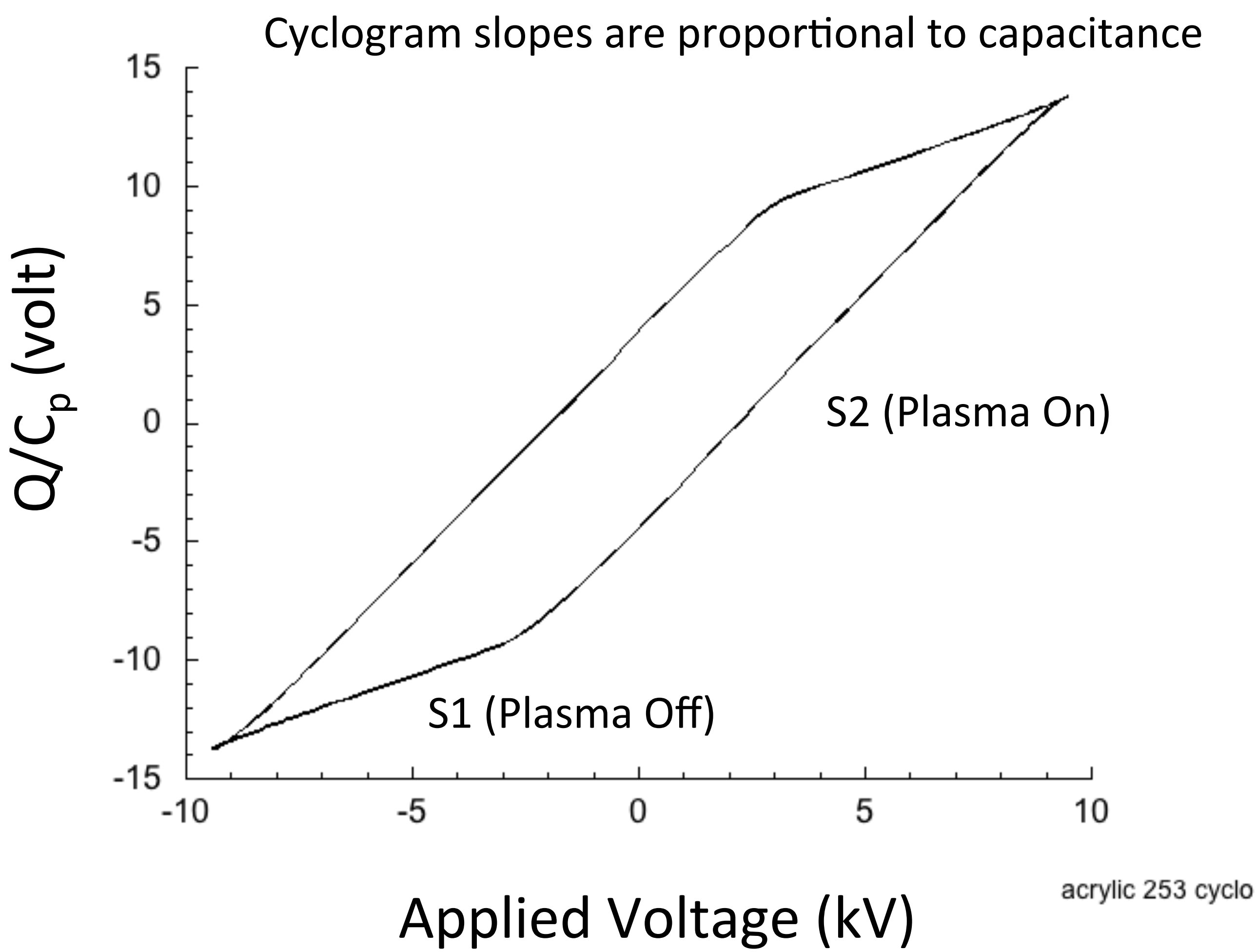

Cyclogram Characteristics for different materials

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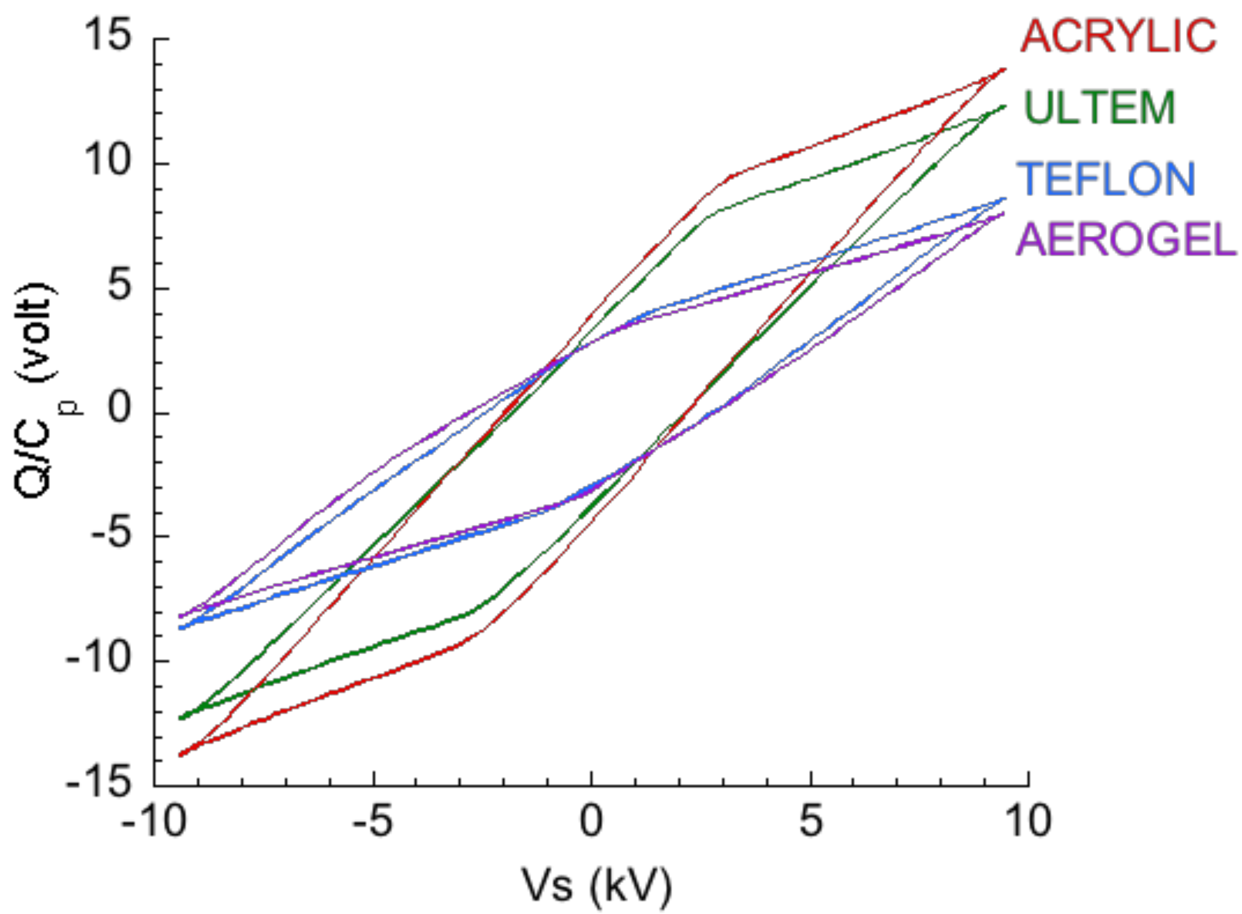
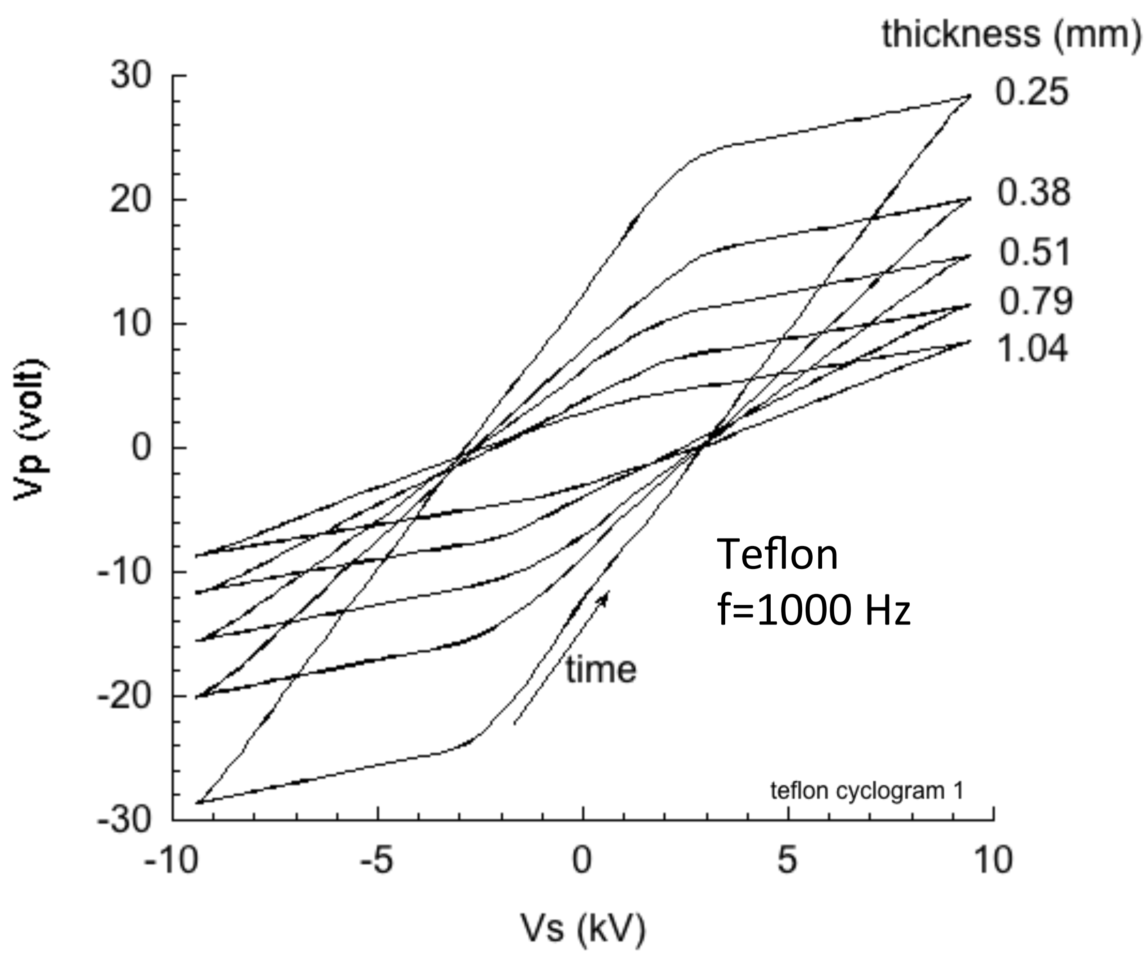


Parametric Analysis of Cyclogram Characteristics (frequency, voltage, gap, thickness, permittivity)



One Dimensional Circuit Simulation of the Actuator Material and Test Environment*

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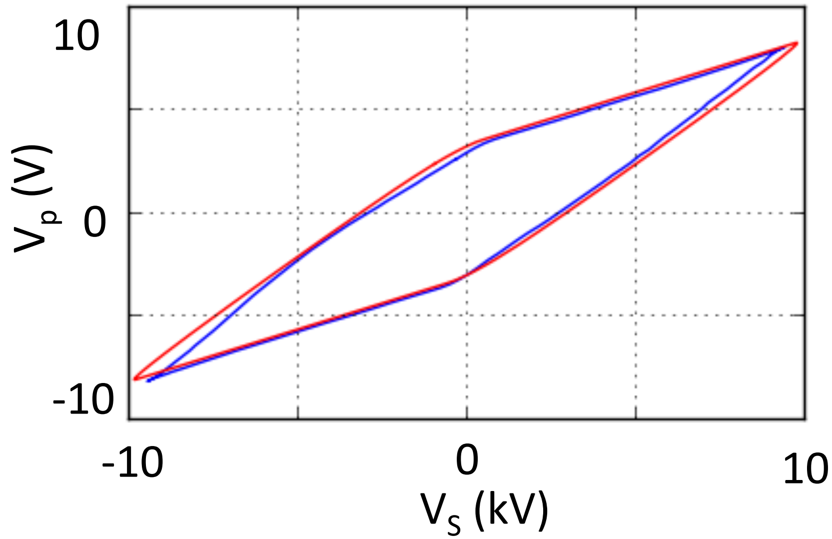
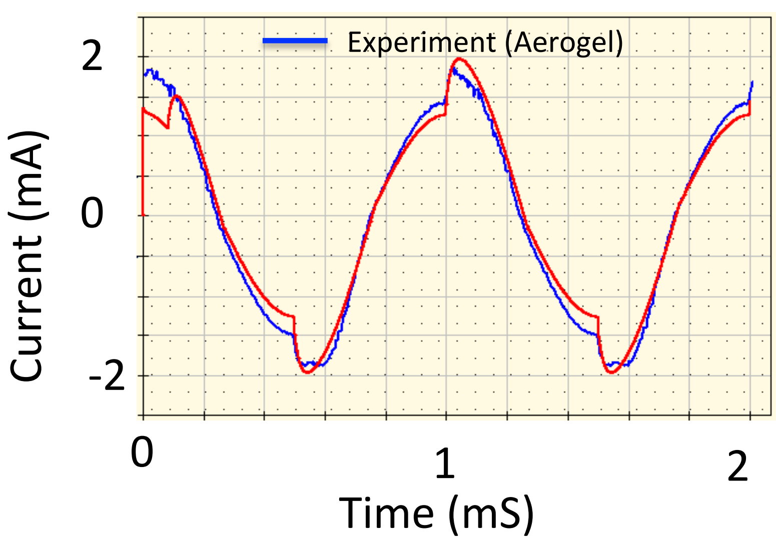
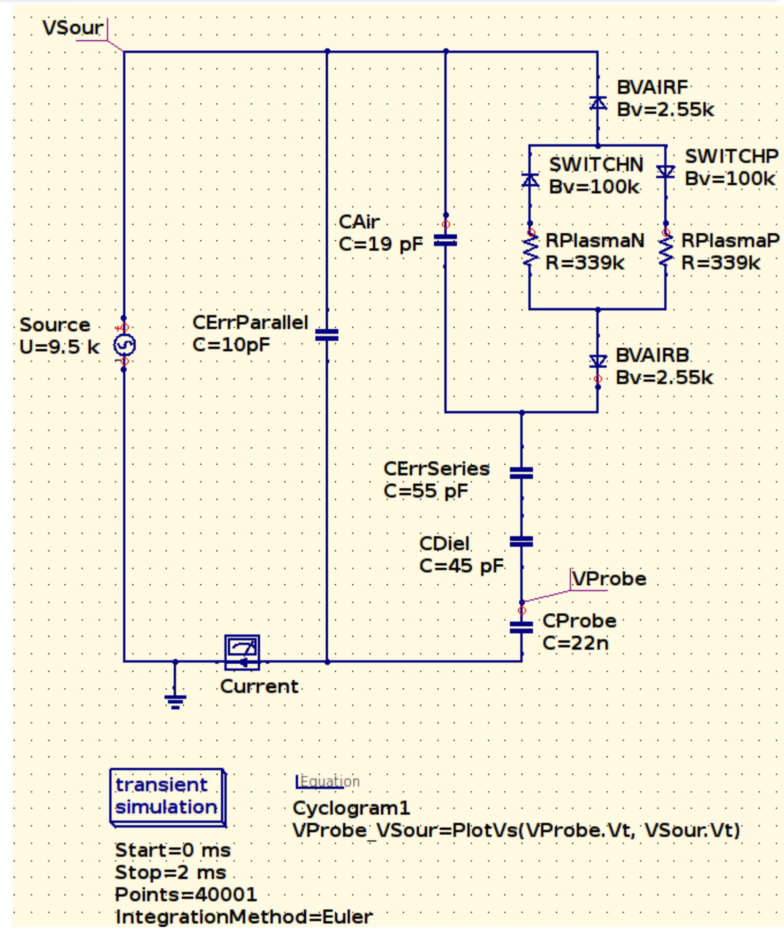






*Data fitting using Qucsator (0.0.18) and SageMath (5.12)

Summary / Conclusions

- Goal 1: Characterize existing dielectric materials seeking to explain differences in body force generation.
  - Implemented dielectric and force diagnostics, surface coatings, circuit simulations and 1D charge transfer technique.
  - Studied a dielectric properties and performance of a variety of organic and inorganic materials.
  - Demonstrated that polyimide aerogels can support a DBD plasma.
  - Measurement uncertainties due to inadequately controlled system electrostatics and variable atmospheric humidity preclude conclusive material assessments at this time.

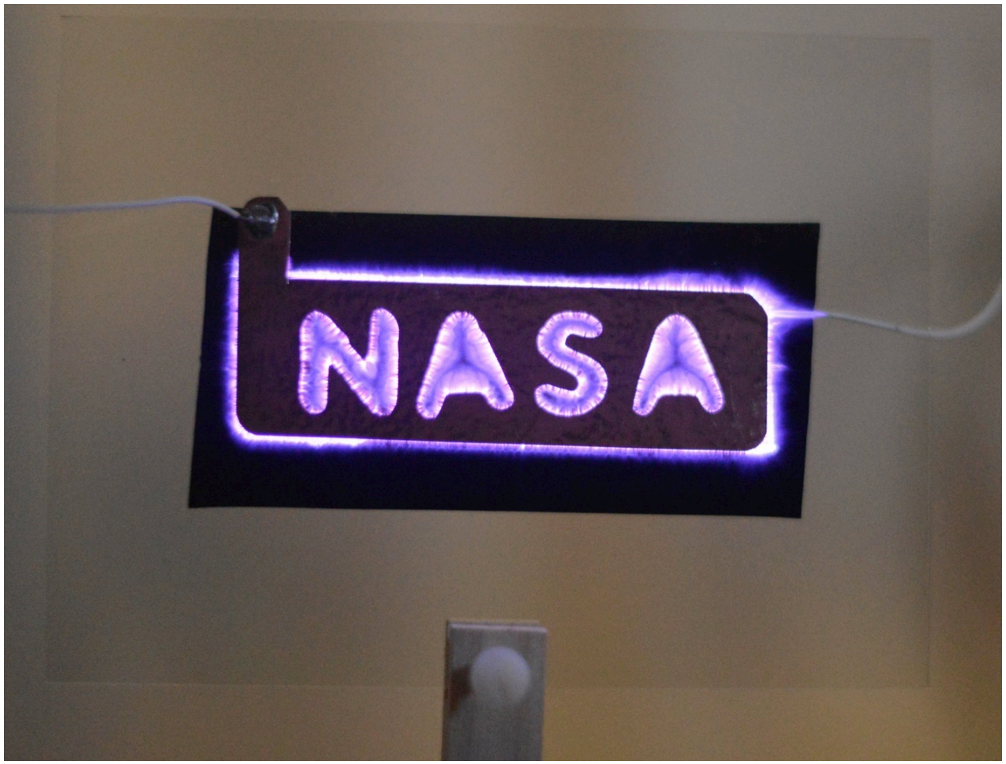
Summary / Conclusions (cont.)

- Goal 2: Use this information to develop new materials optimized for DBD applications.
  - Refined diagnostics with increased resolution and accuracy are required to differentiate DBD responses due solely to bulk permittivity and geometry from those due to possible plasma/surface (material) interaction effects.
  - Higher voltage power supply (> 20kV pp) is required to examine force saturation effects where surface interactions are more likely to be manifest.

Future Directions

- Continue fundamental physics research of DBD dielectric materials.
- Identify specific flow features amenable to active DBD flow control and align DBD research with aeronautical applications
- Provide estimates of the impact of DBD forcing on airplane system energy resources.
- Identify appropriate program(s) within ARMD best suited for DBD research and other related direct, ionized gas flow control concepts (plasma arcs, spark jets, etc.)

And if all else fails: Consider *DBD Art and Music* !



Copper foil on 1.2 mm thick glass
V= 20 kVpp @ 1 kHz
Nikkor 50mm f/1.4 , 1/5 sec exp.

Concept: Ken Miller, Eagle Harbor Technologies, Seattle, WA

Tone scale (C_6)
V=20 kVpp
$1046.5 < f < 2093.0$

END